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Wave induced stress profile on a paired column semisubmersible hull formation for column reinforcement

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ABSTRACT

A study into reinforcing the hull of the recently developed paired column semisubmersible platform has been carried out by understanding the stress profile around its columns from hydrodynamic interaction during survival and extreme weather conditions in the Gulf of Mexico. The conceptualization of this hull system is to enable dry-tree technology on semisubmersibles for deep-sea exploration. Its hydrodynamic response behaviour has been confirmed to be compatible with this technology, although its size and high steel requirement are of major disadvantage. Preliminary CFD study has showed an unusual flow behaviour within and around the hull due to its unique column arrangement. This behaviour creates an unusual hydrodynamic pressure profile on the hull, dominated by the wave parameters. Numerical models were developed using ANSYS and AQWA to compute the stress distribution on the columns from this unique uneven hydrodynamic pressure. The boundary conditions for the FE-model were formulated using hydrostatic stiffness theories and hydrodynamic response plots developed in Orcaflex. The results have showed high stress concentration on the inner columns. For operating conditions (low wave amplitude), the wave propagating direction was observed to have little or no effect on the column stress distribution. Significant effect of the wave propagating angle was observed as its amplitude gradually increases. Results for topside and deck mass effect on the stress distribution on the columns also suggested high stress distribution around the joint area of the inner columns for extreme and survival weather conditions, irrespective of the flow orientation.

1. Introduction

1.1. Overview

Column-stabilized semisubmersibles are the most used type of semisubmersible in ocean engineering. The design employs the use of vertical columns to suspend a superstructure from the waterline, and supported at the bottom with a pontoon system. Deep draft semisubmersible hulls systems are mainly used for designing drilling and production units in the oil and gas industry. The recently developed paired column semisubmersible (PC-Semi) platform for dry tree application has added to the fleet. This newly developed hull system has been reported to have unique motion behaviour in deep-sea, which makes it favourable for deep water production platform design. The uniqueness of its dynamic behaviour has been observed in its wave influenced and vortex-induced motions. Different reports have been presented as an attestation to that fact [1–4]. However, the influence of the wave behaviour on the deformation and stress distribution on the hull has not been studied. The hydrodynamic interactions from wave, current and wind loads sometimes make it difficult to access the strength of large floating bodies.

A literature review was carried out first to understand how wave energy is transferred on floating structures. The theoretical background of this was discussed in [5] in a review of hydroelastic theories for response of marine structures. This review explained in a broad view the development of two and three dimensional (linear and nonlinear) theories used in evaluating fluid structural interactions of deformable parts in marine structures. The text presented in [6] gave a detailed understanding on

Abbreviations: PC-Semi, paired column semisubmersible; ABS, American Bureau of Shipping; DNV, Det Norske Veritas; CFD, Computational Fluid Dynamics; RAO, Response Amplitude Operator; MODU, Mobile Offshore Drilling Unit; FPI, Floating Production Installation; RP, Recommended Practice; DOF, degrees of freedom; API, American Petroleum Institute; RPSEA, Research Partnership to Secure energy for America; FSI, fluid structure interaction.

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Nomenclature

Symbols

ϕ	Velocity potential
P_{hyd}	Hydrodynamic pressure
g	Gravity
ρ	Sea water density
A_w	Wave amplitude
θ	Wave propagating angle
λ	Wave length
ε	Perturbation parameter
∇	Laplace grad operator
H_s	Wave height
z	Draft height
h	Sea depth
ψ_i	Radiation unit amplitude
ϕ_{ir}	Radiation unit velocity potential
ϕ_R	Radiation potential
s_w	Wetted surface
s_w^{avg}	Average area of wetted surface
σ_e	Equivalent stress (von Mises stress)

the motions and deformation experienced in barges and columns under regular wave loading, assuming that the flow was incompressible, inviscid, non-rotational and of small wave amplitude. With these assumptions, mathematical models were generated to calculate the bending and continuous deformation at different mode shapes of a free-free (both ends) submerge floating column and barge. In resolving the hydrodynamics of a single slender vertical column, high resonant deflection was noticed within the range of occurring wave energy. Comparisons for hinge joints and free conditions were analysed for the problem of a floating barge, and the effect of constraints was investigated for certain degrees of freedom [7] described the hydrodynamic nature of fluid interactions between a set of arranged columns supporting a large flexible structure (pontoon). He resolved the motion equations of the topside integral part considering the effect the trapped wave and flow circulation within the columns, and the possible effects of stress and elastic deflection of these on the topside. Solutions of this problem require dealing with complex issues such as, flow separation and boundary layer shear. Diffraction analysis is the most effective way to resolve this problem (evaluating the wave effect on floating structures), without having to deal with the above mentioned complex issues. [8]made progressive contributions in resolving the diffraction problems experienced with multiple floating structures in directional waves using finite element method. Their analysis was focused on structural response investigation in regular wave with small amplitude, and they were able to make significant conclusions on the relationship between force and response ratio criteria. Although the results of their analysis might not have a wide range of application in real life scenarios, its detail presentation served as a significant prerequisite for this study. [9]studied the fluid-structure interaction (FSI) of three-dimensional bodies in water waves and were able to develop an interaction theory that effectively predicted the diffraction characteristics of each member of the body.

Early studies on PC-Semi showed that the column plate deformation was due to a number of factors that actually varied with wave height (Hs) and its orientation. Results recorded in [10] highlighted some factors e.g., column shape, second moment of area, drag force coefficient, draft size and plate thickness that are most likely to alter the extent to which the column plates will deform from hydrodynamic loadings in rough weather. From the systematic literature review, alongside a preliminary CFD study, the unique arrangement of columns was observed to create flow circulation within the hull structure which in turn generates an uneven drag around the columns. The wave also experiences an asymmetric relationship in the space within the eight columns, creating an uneven stress profile around them, which is greatly influenced by the uneven hydrodynamic pressure distribution that is exerted from wave-current interactions. These circulations coupled with the wave loads create an unusual loading on the columns which results in deformation of the hull. The strength of floating hulls is determined from their buckling tendencies and stress distribution, providing information on where necessary reinforcement were required.

This paper introduces a research study on how column reinforcement can be carried out on a paired column semisubmersible platform subjected to the stress profile from the wave loads specified in DNV and ABS standards. In this study, we described the nature and effect of wave-induced stress profile on the columns of a PC-Semi, using a finite element approach. The study also provides a detailed analysis on the factors influencing the uneven hydrodynamic force parameters on the hull of a PC-Semi. The wave load and boundary conditions used for formulating the FE-model were extracted from hydrodynamic models developed in AQWA and Orcaflex. At the end of this study, areas requiring high steel reinforcement are identified, to guarantee the safety of the hull under twisting and bending phenomenon.

1.2. Hull description

A typical PC-Semi is made of eight rectangular columns, (four inner columns and four outer columns), a topside, pontoon, inner-outer column connections, and inner column braces. The inner columns are slightly smaller than the outer ones, to reduce the oscillating amplitude of the shed vortexes during high current velocities [11]. Fig. 1 shows the geometry adopted in this study, which was extracted from [12]. The inner and outer columns are 14.0 m × 10.40 m and 14.0 m × 13.40 m respectively. The edges of the columns were designed with a fillet curve of 2.01 m radius, which reduced the respective diagonal distance of the columns to 17.72 m and 15.60 m. This reductions alter the effect of vortex shedding phenomenon on this hull, details of which will be presented in subsequent sections. The curved edges also help to distribute the stresses around the plates. The columns on each pair are 20.4 m apart from their base.

2. Theory formation

2.1. Hydrodynamics

For large floating bodies such as a PC-Semi hull, a good understanding of the diffracted and radiation wave conditions are required to describe the dynamic effect of the fluid structure interactions on the strength and stability of the columns. Hydrodynamic correlations were used to estimate the flow pressure and force parameters in this study. The correlations are based on the resolution of fluid potential of a free floating body with six degrees of freedom. For an irrotational, incompressible and inviscid fluid,